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Abstract

Using three-hour average values of the bulk speed V and the proton temperature T of the solar wind, derived from observations conducted on the satellite Explorer 34, it is shown that

$$T^{\frac{1}{2}} = (.036 \pm .003)\ V - (5.54 \pm 1.50)$$

where V is in km/sec and T in kilo-degrees Kelvin. Results from other experiments at different parts in the solar cycle are also consistent with this relation. The V-T relation puts an important constraint on solar wind theories.

The 2-fluid model of Hartle and Sturrock, which does not include effects of non-thermal heating, gives values of V and T which are consistent with the above V-T relation at quiet times. Thus, non-thermal heating at quiet times is unnecessary and would be inconsistent with this theory.

We have searched for evidence of non-thermal heating which depends on velocity gradients at 1 AU. It is shown to be absent at negative gradients, indicating that the Kelvin-Helmholtz instability is not a significant source of heating in the solar wind. Local proton heating does occur at large positive gradients. We attribute this to turbulence generated by the collision of fast streams with slow plasma. Such heating is very localized, however, and not the major source of thermal energy. This suggests that turbulence, as opposed to fluctuations, occurs only in "patches" and is not a large scale phenomenon near 1 AU. Heating by shocks is found to be a very small effect on a large scale.

There is still no satisifactory theory which gives the high-temperatures and high speeds which are observed. Since there is no evidence for large-scale gradient-dependent heating near 1 AU, one is led to the

hypothesis that the high temperatures and high speeds are both due to an extended heat source near the sun. Some results are presented which support the view that the solar wind can be described by a 2-fluid model with extended heating by hydromagnetic waves near the sun as proposed by Barnes; a quantitative formulation of this model is needed.

I. Introduction

This paper describes a study in which satellite observations of the solar plasma are used to determine the relative importance of the various energy sources which have been proposed to heat it. The proposed sources can be classified according to the region where the heating is assumed to occur: a) at the base of the corona, b) in an extended region up to 50 $R_\odot$ from the sun, and c) in the interplanetary medium.

The base of the corona, which has a temperature $(1 \text{ to } 2)\times 10^6\ {}^\circ K$ is an established heat source, agreed upon by everyone. However, unless the proton thermal conductivity is much higher than generally believed, the protons would tend to cool, by adiabatic expansion as they move from the sun, to temperatures far below those which are observed at the earth. Thus, an additional heat source operating at some distance from the sun is required.

Heating of protons and electrons out to several radii has been considered by Parker (1963), and it was shown that reasonable representative solar wind temperatures and speeds can be predicted in this way. Barnes (1968) has recently proposed that heating is produced by the damping of hydromagnetic waves propagating from the sun.

Two types of proton heating in the interplanetary medium have been suggested: a) heating by collision with electrons, which are maintained at a high temperature by the conduction of heat from the base of the corona. This introduces explicitly the electrons, whose presence was implicit in earlier treatments to give charge neutrality. Theories in which protons and electrons are assumed to be at the same

temperature must be distinguished from the two-fluid theory (Sturrock and Hartle, 1966; Hartle and Sturrock,1968) where the species are assumed to interact only weakly; b) heating by hydromagnetic waves which are presumed to be generated by "turbulence" at velocity gradients. The latter mechanism was proposed by Coleman (1968) and by Jokipii and Davis (1968) when Sturrock and Hartle showed that the transfer of energy from electrons to protons is not as effective as assumed in the 1-fluid, conduction models of Parker (1963), Whang and Chang (1965), Whang, Liu and Chang (1966), Noble and Scarf (1963) and others.

We shall first consider the general observations of proton, electron and alpha particle temperatures, since they are of central importance in any heating theory. The proton temperature T is known to vary with the bulk speed V (Neugebauer and Snyder, 1966). We show that there is a simple, quantitative relation between $T^{\frac{1}{2}}$ and V, and we emphasize the importance of this relation with regard to solar wind theories. Some recent electron temperature (T_e) measurements are collected below; they show that T_e does not vary appreciably with V, implying that protons and electrons are not heated in the same way. Some additional evidence that $T\alpha$ (alpha particle temperature) is nearly 4T is also presented.

Models with heating by conduction out to 1 AU. give sufficient thermal energy at 1 AU during quiet times (extremely low V), but only the 2-fluid model predicts the correct distribution of energy between protons and electrons.

None of the models with a heat source only at the base of the

corona predicts the high speeds and the high temperatures which are observed at non-quiet times.

We examine the hypothesis that high temperatures are due to processes which depend on gradients in the bulk speed near 1 AU. Such heating is found only in the vicinity of isolated, large, positive gradients, and is thus not a dominant, large-scale heat source. It is suggested that turbulence, as distinct from fluctuations, occurs only in "patches", and is not a large-scale phenomenon near 1 AU.

We examine the hypothesis that high speeds are produced by heating caused by the damping of hydromagnetic waves in the region from ~ 1 to $\sim 50\ R_{\odot}$, as suggested by Barnes (1968). We present some support for this hypothesis, but a quantitative treatment in the framework of the 2-fluid theory is needed to show that it can produce both high speeds and high temperatures in accordance with the V-T relation.

Most of the observations to be described below were made by the GSFC - University of Maryland plasma experiment on Explorer 34. Both the instrument, and the methods of data reduction used, have been described before, (Ogilvie, McIlwraith and Wilkerson, 1968; Ogilvie, Burlaga and Richardson, 1967) and will not be discussed here.

II. Temperature of the Solar Wind

a) Definition. Because of the long collisional mean free path in interplanetary space, it is not obvious that the concept of temperature is applicable to the solar wind. The observed temperatures which are quoted in the literature are actually measures of the width of the distribution function f(v) for protons, where v is the total speed. Most measurements do not determine f(v) very precisely since they are based on energy spectra with only a few bars in most cases. Nevertheless, the instruments measure similar spectra, and one would expect to find comparable "temperatures" if a uniform method of deriving T from f(v) were used. Most workers assume that f(v) is an isotropic maxwellian distribution and fit the observed spectra with this function to get the maxwellian temperature. The temperatures derived from Vela and Explorer 34 observations are not derived on this assumption. The latter are defined in terms of the moments of an empirical, quasi-maxwellian distribution which gives the correct temperature when f(v) is maxwellian (see Ogilvie et al. 1967, Burlaga and Ogilvie (1968) for details). Thus, the temperatures are all comparable if the actual distributions are maxwellian to zeroth order, which seems to be the case (Hundhausen, 1968).

It is known that the proton temperature of the solar wind is not isotropic, and that the temperature parallel to the magnetic field (assuming a bi-maxwellian distribution) is, on the average, approximately twice the temperature perpendicular to the interplanetary magnetic field, $\underset{\sim}{B}$. The Explorer 34 instrument measures the temperature along the earth sun-line, which should be intermediate between $T_{\parallel}$ and $T_{\perp}$ on

the average, because $\underset{\sim}{B}$ usually makes a 45° angle with the radial direction. Since we are concerned in this paper with the gross variations of the temperature which ranges from $\lesssim 10^{4}\,{}^{\circ}K$ to $>10^{6}\,{}^{\circ}K$, the uncertainty of a factor of ~ 1.5 due to the anisotropy is of little consequence in what follows.

b) <u>Observations of the Interplanetary Proton Temperatures</u>. Figure 1 shows the distribution of the 3-hour averages of the proton temperatures measured by the Explorer 34 plasma experiment in the interval June 3 to December 16, 1967. The most probable temperature is $(4.6 \pm .5) \times 10^{4}\,{}^{\circ}K$, which is in good agreement with that reported by Coon (1968) for the period July 1964 - July 1965, namely $4.8 \times 10^{4}\,{}^{\circ}K$. The temperature ranges from $<10^{4}\,{}^{\circ}K$ to $8 \times 10^{5}\,{}^{\circ}K$. This variability is illustrated in Figure 2 which shows a plot of the Explorer 34 3-hour averages of T as a function of time. <u>Both</u> of these characteristics - the most probable temperature and the variability of T with time are fundamental properties of the solar wind which must be explained by a satisfactory theory. Ultimately, of course, one would hope for a theory which predicts the temperature distribution given in Figure 1.

c) <u>Observations of the Interplanetary Electron Temperatures</u>. Because of their high thermal conductivity, it is possible that electrons effectively transfer heat from the sun to the distant interplanetary medium and heat the protons. Thus, an understanding of the proton temperature depends to some extent on a knowledge of the electron temperature. Unfortunately, few direct measurements of the electron temperature, T_e, are available, but Table I summarizes

some current observations. The observations by Wolfe and McKibben (1968) made when the wind speed was very low (290 km/sec), give $T_e \sim 2 \times 10^5 \, ^oK$ and $T_e/T \sim 5$, which may be uncertain by a factor of 2. Burlaga (1968) used an indirect method involving pressure balance across tangential discontinuities to show that $T_e/T \gtrsim 4$ and $T_e \gtrsim 10^5 \, ^oK$, when $V \sim 350$ km/sec. Montgomery et al. (1968) found $T_e = .9 \times 10^5 \, ^oK$ to $1.5 \times 10^5 \, ^oK$ when $V = 400$ km/sec; the corresponding T_e/T_p ranged from ~ 1.5 to ~ 3. Bame et al. (1969), in a preliminary report gave $T_e/T \approx 3$ at a time when Ogilvie, Burlaga and Wilkerson (1968) reported $T \sim 5 \times 10^4 \, ^oK$ and $V = 385$ km/sec; this gives $T_e \sim 1.5 \times 10^5$ at $V = 385$ km/sec. Ogilvie and Ness (1969) used an indirect method to infer that $T_e/T \sim 2$ over an extended period of time when the average speed was $V \sim 400$ km/sec. Finally, Bame et al. (1969) reported that when $V > 400$ km/sec, $T_e/T \sim 1$. Thus, the observations suggest that T_e/T is bulk speed dependent, and decreases with increasing V. It is clearly important to study this relation further. Note that all of these measurements give $T_e \sim (1.5 \pm .5) \times 10^5 \, ^oK$. This suggests that the electron temperature may be nearly independent of V. This is consistent with the result of Montgomery et al. (1968) that the electron temperature varied much less than the proton temperature during a two month period, and ranged from $7 \times 10^4 \, ^oK$ to $2 \times 10^5 \, ^oK$.

d) Alpha-Particle Temperature Measurements. Observations of the temperature of H_e^{++} in the solar wind have been reported which suggest that, on the average, T_{α}/T is between 3 and 4. (Robbins et al. 1969, Ogilvie and Wilkerson, 1969). Observations of these ions allow us to infer something about heating processes in the solar wind, because, as pointed out by Jokipii and Davis (1968), a process which causes the change in the velocity distribution function depending only upon the particle velocity, will give all ions the same velocity distribution and temperatures proportional to their masses. Thus, observations showing that $T_{\alpha}/T \simeq 4$ are consistent with heating by hydromagnetic waves, while equal temperatures would be consistent with collisional heating leading to thermal equilibrium. Such observations cannot tell us, however, where the heating took place.

The Explorer 34 observations of helium were hampered by the presence of an instrumental background, so that the temperatures are the least accurately known quantities for the most part. We therefore only have accurate ratios T_{α}/T for periods of time when the densities of Helium and Hydrogen were high. Several of these times coincided with velocity gradients shown in Figures 2a and 2b; the observations are set out in Table II. The mean value of T_{α}/T is 3.75, equal to four to the limits of experimental error, and this observation therefore supports the idea of non-collisional heating near large positive velocity gradients.

e) Relationship Between T and V. A qualitative relation between V and T was noted by Snyder and Neugebauer (1966). To examine the relation between speed and temperature of the solar wind quantitatively,

we have taken 1096 3-hour averages of V and T from Explorer 34 and computed th average temperature, $\bar{T}$, for the intervals with 250 km/sec $<v<$ 300 km/sec, 300 km/sec $<v<$ 350 km/sec, etc. The results are represented by the open circles in Figure 3. The points lie close to the line

$$\sqrt{T} = aV-b \qquad (1)$$

with a=.036 ±.003 and b=5.538 ±1.50

It should be noted that (1) is not a unique fit to the observations. They can for example, be described by the equation $V^2 = m+nT$, which is suggested by the Bernoulli equation (Parker 1963) with $T_\odot \propto T$. However, (1) seems to be a somewhat better fit and is used in the calculations below. Agreement with this simple empirical relation is a rather remarkable fact, for it applies to <u>all</u> of the Explorer 34 data, which extend over the range 250 km/sec to 750 km/sec. The uncertainty in $\bar{T}$, determined by computing the variance of the values of T in a given velocity interval, is indicated by the error bar at the point with the highest T.

It is of interest of compare the Explorer 34 observations of T and V with those made by other instruments at different times in the solar cycle. Hundhausen (1968) gives V=320 km/sec and $T=4\times10^4$ °K for quiet times in the period 1962-1967. This point is plotted as the letter H in Figure 3. Wolfe and McKibben studied a very "quiet" period shortly after the launch of Pioneer 6 on Dec. 15, 1965 and found $T_\perp \approx 10^4$, $T_\parallel \approx 4\times10^4$ and V=265 km/sec; the value of T is between $T_\perp$ and $T_\parallel$, which are shown by the limits of the bar marked W in Figure 3. Average values of $\sqrt{T}$ and V measured by Neugebauer and Snyder for the duration of the flight of Mariner II in 1962 are

given by the point N in Figure 3. It can be seen that all of these measurements are in excellent agreement with the Explorer 34 measurements. Thus, the relation $\sqrt{T}$ = .036V-5.54 appears to describe a fundamental characteristic of the solar wind.

Figure 3 also shows theoretical values for T and V. The letters V, W and N' are the predictions of Whang, Liu and Chang (1966), Whang and Chang (1965) and Noble and Scarf (1963), respectively, based on a 1-fluid model with heat conduction. Results of Parker's isothermal model (Parker, 1963) are shown by the solid dots.

III. Heating Mechanisms

a) Proton Heating by Collisions with Electrons

With the data presented in the previous section as a basis for discussion, we shall now turn to the various theoretical ideas which have been explored in attempts to solve the problem of the heating of the solar wind. The most extensively developed idea is that electrons conduct a large amount of thermal energy from the sun and protons acquire part of this energy by coulomb interaction with the electrons. In the work of Whang and Chang, Whang, Liu and Chang, and Noble and Scarf, the assumption is made that $T=T_e$, as in an ordinary, collision-dominated plasma. Sturrock and Hartle have pointed out that this assumption is not justified in the solar wind because the mean free path for energy exchange is very large. In their model, protons and electrons behave as separate fluids, which are only weakly coupled by the term $(3/2)\nu_E nk\,(T_e-T)$ where ν_E is the energy-exchange rate between protons and electrons with density n. Of the presently developed models which assume that heat is supplied only at the base of the corona, all require that the solution fit the Blackwell (1956) electron densities at the sun.

When the energy exchange is treated by the 2-fluid model, it is found that the electrons conduct nearly the same amount of energy from the base of the corona as is predicted by the 1-fluid models, but only a small fraction of this is acquired by the protons. Specifically, the 2-fluid model predicts $T_e+T=3.5\times10^{5}\,^{o}K$ and, $T_e/T=80$ at 1 AU. when V=250 km/sec, while the 1-fluid model of Whang and Chang predicts $T_e+T=3.5\times10^{5}\,^{o}K$ and, of course, $T_e/T=1$ when V=260 km/sec. Two theoretical values of (V,T), computed by Hartle

and Sturrock using the 2-fluid model, are shown by the crosses in Figure 3. These predictions are in good agreement with the extrapolated observations. It is not possible to directly compare the predicted electron temperature with observations, because there are no electron measurements at $V \leq 250$ km/sec and there is no established relation between V and T_e. However, the results in Section II suggest that T_e does not vary appreciably with V when $V<400$ km/sec and that the observed $T_e \sim 1.5 \times 10^5 \,^oK$ at $V>300$ km/sec is not far from the predicted value $T_e \sim 3.5 \times 10^5 \,^oK$ at $V = 250$ km/sec. Thus, the 2-fluid model does provide a satisfactory explanation for the "quiet" solar wind ($V \lesssim 250$ km/sec.) It should be emphasized, however, that the "quiet" solar wind is not a special, well-defined state of the solar wind, but rather an unusual and extreme condition. This is demonstrated in Figure 4, which shows the distribution of 3-hour averages of V from the Explorer 34 data.

At Hartle and Sturrock have noted, their 2-fluid model cannot give the high temperatures and speeds which are normally observed. Several authors have concentrated on the problem of the low temperatures and proposed interplanetary heating mechanisms, which we discuss in the next section. However, it should be noted that $k(T_e+T) \ll mV^2$. Thus, the low V is a more serious problem than the low T.

b) Turbulent Heating

Recently, Coleman (1968) and Jokipii and Davis (1968) proposed that the dominant source of thermal energy in the solar wind is the damping of hydromagnetic waves generated at velocity gradients near 1 AU. Jokipii and Davis suggested that the hydromagnetic

waves would damp by Barnes mechanism (Barnes, 1966) and heat both the protons and alpha particles, and they made the important point that such damping heats the alpha particles to a temperature four times that of the protons. Coleman suggested that the hydromagnetic wave energy would cascade from longer to shorter wavelengths in analogy to ordinary turbulence, and would ultimately be transferred to the protons by cyclotron resonance. The word "turbulence" has been used both to describe this condition, and also to describe the random velocity field suggested by Jokipii and Davis.

It should be noted that these hydromagnetic heating theories are based on the suggestion that hydromagnetic waves are continually generated at velocity gradients in the interplanetary medium. They do not show how hydromagnetic waves are generated at velocity gradients, and they do not attempt to explain the origin of the high wind speeds which are required for the proposed turbulent heating. In the next section we consider the hypothesis that the process which gives the high speeds may also give the high temperatures, making large-scale turbulent heating near 1 AU. unnecessary.

In this section we shall show that if the $\sqrt{T}$-V relation is the result of processes near the sun, then there is evidence that some additional heating does occur near large positive velocity gradients at 1 AU., but not near large negative gradients.

We define the bulk speed "gradient" by the equation

$$\Delta V = V(t+3\text{ hr}) - V(t),$$

where V(t) is the mean speed for a 3-hour interval centered at time t.

A negative gradient implies that the bulk speed measured at

the spacecraft appeared to be decreasing with time. Assuming a nearly stationary state, such a decrease represents the entry into a region with lower V, i.e. $dV/dt < 0 \Rightarrow \partial V/\partial t + \underline{V}\cdot\Delta\underline{V} \approx V\cdot\Delta V < 0$. We define a region of local heating as one in which $\Delta T \gtrsim 10^5 \,^{\circ}K$, where

$$\Delta T = \overline{T} - (.036\overline{V} - 5.538)^2,$$

with $\overline{T} = [T(t+3\text{ hr}) + T(t)]/2$ and $\overline{V} = [V(t+3\text{ hr}) + V(t)]/2$.

Now let us consider whether there is local heating near large positive bulk speed gradients. Figure 5 shows the normalized distribution of the ΔT's for $\Delta V > 0$, based on the Explorer 34 3-hour averages of V and T. The points actually represent histogram bars for $0 < \Delta T < 50\times10^3 \,^{\circ}K$, $50\times10^3 \,^{\circ}K < \Delta T < 100\times10^3 \,^{\circ}K$, etc. The solid curve shows that a) the ΔT's for $\Delta V > 0$ are nearly symmetrically distributed about $\Delta T = 0$, as would be expected if the distribution simply represents the scatter of points about $\overline{T}$, but b) there is some indication that there are more positive ΔT's than negative ΔT's. To examine the possibility that local heating was occurring near the largest bulk speed gradients, we computed the ΔT distribution for the cases $\Delta V \leq 15$ km/sec, ≤ 30 km/sec, and ≤ 45 km/sec. The results, shown in the right panel of Figure 5, clearly indicate that the local heating occurs at large positive gradients. The fraction of intervals with $\Delta T < 0$ systematically decreases as ΔV increases, and the fraction of intervals with $\Delta T \sim 10^5 \,^{\circ}K$ systematically increases with ΔV.

Two heating mechanisms have been suggested - the Kelvin-Helmholtz (K-H) instability (Parker 1963) and the collision of fast stream with slower plasma (Sarabhai 1963). We cannot exclude the K-H instability as a cause of heating at the largest positive gradients. But if the K-H instability were the cause of the heating which is seen at positive gradients, heating should be seen at negative gradients of comparable magnitude. The left panel of Figure 5, which shows the ΔT distribution for $\Delta V<0$, <-15 km/sec, <-30 km/sec, and <-45 km/sec, gives no evidence for heating at negative gradients. We infer that the heating at positive gradients is not due to the K-H instability. It is reasonable to attribute the heating to colliding streams.

Having demonstrated that large $\Delta V>0$ are associated with $\Delta T \gtrsim 10^5$ °K, let us now inquire whether the converse is true, i.e. whether "hot spots" (regions with $\Delta T \gtrsim 10^5$ °) are all associated with large $\Delta V>0$. We have found 25 "hot spots" in the Explorer 34 data, indicated by the horizontal lines in Figure 2. Seventeen of the "hot spots" are clearly associated with large positive ΔV. Three are associated with negative ΔV, but two of these are short intervals and have ΔT very near 10^5 °K, so they may not be statistically significant. Five are not clearly associated with either a positive or a negative ΔV, and two of these are short intervals with ΔT near 10^5 °K. Thus, "hot spots" are usually found in the vicinity of large positive bulk speed gradients.

Shocks are known to heat the solar wind, they are associated with positive bulk speed gradients, and at least 13 shocks have been identified in the Explorer 34 data by Burlaga and Ogilvie (1969),

so they could conceivably form a significant part of the heating which is observed. The times at which the shocks were observed are indicated by the triangles in Figure 2. Note that only 5 of the 25 hot spots ($\Delta T > 10^{5}\,{}^{o}K$) are associated with shocks; furthermore, 2 of the 5 do not immediately follow a shock, suggesting that they were not caused by shocks. Thus, shocks are not the principal cause of the hot spots which were observed by Explorer 34. This leaves collisional interactions of fast streams with slow streams as the most likely cause of the heating.

We now ask whether heating at positive gradients is a dominant macroscale solar wind heat source. To answer this question, we have compared the ΔT distribution for $\Delta V>0$, which does show local heating with the ΔT distribution for $\Delta V<0$, which does not show local heating (see Figure 6a). It is seen that to zeroth order the distributions are the same, although a small effect of heating at $\Delta V>0$ is evident. Figure 6b compares the distribution for $0<\Delta V<15$ km/sec with that for -15 km/sec $<\Delta V<0$, and shows that they are virtually identical, implying that the small heating seen in Figure 6a is the result of $\Delta V>15$ km/sec. The conclusion is that heating at positive bulk speed gradients is not a dominant macroscale heat-source. The reason that local heating is not very significant on a large scale is that large gradients seldom occur. The latter fact is demonstrated in Figure 7, which shows the distribution of the ΔV's for the Explorer 34 data. This figure illustrates two additional important facts: a) the distribution of <u>all</u> the ΔV's is well described by a single simple relation, suggesting once again that the variability is a

general statistical property of the solar wind which can be treated by a relatively simple theory, b) the curves for positive and negative gradients have different slopes and indicate that the positive gradients tend to be steeper than the negative gradients.

Although the above discussion shows that colliding streams are not a dominant macroscale solar wind heat source, there is still the possibility that the high mean temperatures are produced by some other interplanetary heating process. This process does not depend on velocity gradients, since a larger negative gradient at a given V does not imply a higher temperature. Let us assume for the moment that such a process exists and ask whether it is consistent with the existing solar wind theories. Clearly, such heating is inconsistent with the 2-fluid model, because the 2-fluid model does predict the correct proton temperature at $V \lesssim 250$ km/sec; additional heating by turbulence would give temperatures that are too high. Now consider the possibility that turbulent heating is effective when $250 \lesssim V \lesssim 350$ km/sec. The 1-fluid models of Whang and Chang and Noble and Scarf predict proton temperatures more than 5 times higher than observed (see figure 1) and electron temperatures which are on the order of twice the observed temperatures. Thus, thermal conduction as given by the Chapman-Spitzer formula is more than adequate to account for the observed temperatures. Turbulent heating would only make matters worse. We cannot rule out the possibility that turbulent heating is important at speeds >400 km/sec. However, the linear relationship in Figure 3, which extends over the entire range of bulk speeds, suggests that the same (non-turbulent)

heating mechanism is dominant at all speeds. An extended 2-fluid theory which explains the high wind speeds is needed to settle the matter.

It has been suggested that the solar wind might be turbulent because the Reynolds number, $R=\rho vD/m$ (where D is the scale size $\sim 10^{13}$ cm, ρ the mass density and m=viscosity $\sim 1.2\times 10^{-16}\ T^{5/2}$ gm/cm sec) is $\sim 10^{3}$ between high speed streams. This ignores the stabilizing effect of the magnetic field and the smaller scale size, $\lesssim .01$ AU, introduced by the presence of discontinuities. Using $L\sim .01$ AU, n=5, v=400 km/sec and $T\sim 10^{5}\,^{o}K$ one finds R=.08

IV. Extended Heating Near the Sun

Approaching the problem of successfully predicting the range of temperatures and flow velocities in the solar wind from the point of view of the relation between V and $\sqrt{T}$ discussed above, it becomes clear that the major defect of existing theories is that they do not give sufficiently high bulk speeds. Parker (1963) was the first to point out that if heat were to be added so that the temperature close to the sun remained constant out to a radius R_1 of order twenty solar radii, and if particles cooled adiabatically beyond this distance, very high wind speeds could be produced. Barnes (1968) has recently proposed that hydromagnetic wave damping could give the necessary heating out to tens of solar radii. Jokipii and Davis (1968) have pointed out that such heating gives $T_\alpha/T \sim 4$, and adiabatic cooling beyond the heat source would not affect this ratio, so such a theory would be consistent with the observed T_α/T ratio. It remains to be shown, then, that sufficiently high temperatures and the $\sqrt{T}$-V relation can be explained this way. Using Parkers' (1963) calculated values of V and n at R_1 for a model with an extended heat source, we arrive at the values of V and T set out in Table III, assuming $T_1 = 1\text{x}10^6\,^\circ K$ (Newkirk (1967)) in the region out to radius R_1, which is given in terms of the reference level from which coronal expansion is supposed to start.

In view of the fact that these values diverge so little from the observed temperatures, and of the large number of approximations and assumptions made in this treatment, the extended heating hypothesis cannot be ruled out. However, Parkers' model does not completely solve the problem, since it predicts densities 10 times

the observed densities. A fuller theoretical treatment is needed to determine whether extended heating near the sun can give the V-T relation and the observed densities. Since $T_e \sim$ constant, independent of V (Table I) while T does depend on V, a 2-fluid model will be required. The electron temperatures can be explained by conduction, as shown in Section III, so only the protons need be heated by the extended source. This could be obtained by Barnes' mechanism.

V . Summary

We have emphasized that the variability of the bulk speed, V, and proton temperature, T, is an essential characteristic of the solar wind. On a large scale this variability appears to be governed by rather simple laws. It is shown that the distribution of positive and negative bulk speed gradients is an exponential function which is presumably the result of random processes at the sun. Particularly important with regard to the problem of solar wind heating is a simple quantitative relation between V and T, namely $T = aV+b$. This is satisfied by all of the interplanetary data from Explorer 34 for speeds ranging from 250 km/sec to 750 km/sec and also by data from other experiments at different times in the solar cycle. This V-T relation puts an important constraint upon solar wind theory.

The predictions of Hartle and Sturrock are consistent with the V-T relation and with the observed electron temperatures which appear to be nearly independent of V. In other words the 2-fluid model does not seriously conflict with experiment as some writers have assumed. It becomes clear that Sturrock and Hartle were correct in stating that their model describes only an extreme and unusual state of the solar wind corresponding to very low bulk speeds and gives the correct temperatures for these speeds. Heating by turbulence or by the transfer of large amounts of energy from electrons to protons at low V would give proton temperatures which are too high.

Thus, we infer that nonthermal interplanetary heating is not a significant macroscale process in the quiet solar wind.

If turbulent heating did occur on a large scale in the non-quiet wind as a result of bulk-speed gradients, one would expect it to be largest in the vicinity of the largest gradients, both positive and negative. We find no evidence for exceptionally high temperatures near large negative bulk speed gradients. This argues against the turbulent heating hypothesis and, in particular, it argues against the Kelvin-Helmholtz instability as a significant source of heating in the solar wind. This result is consistent with the work of Burlaga which shows that stresses in the solar wind can be relieved by stable gliding motions along the surfaces of numerous hydromagnetic tangential discontinuities in the solar wind.

It is shown that appreciable heating does occur in the vicinity of large positive bulk-speed gradients. Since it occurs at positive but not negative gradients, it cannot be the result of a velocity shear; however, it is consistent with the idea that heat is generated by the collision of a fast stream with slower moving plasma. We find that temperatures $\sim 2 \times 10^{5}\,^{\circ}K$ are generated in regions where $\frac{dV}{dx} \sim \frac{50 \text{ km/sec}}{.05 \text{ AU}}$. However, such large gradients seldom occur. Moreover, the average temperature at positive gradients ($(1.4 \pm .3) \times 10^{5}\,^{\circ}K$) does not greatly exceed that at negative gradients ($(1.1 \pm .2) \times 10^{5}\,^{\circ}K$). Thus, we conclude that such collision-heating is not a dominant heating process on a large scale. It is shown that shocks were even less effective in heating the solar wind during 1967 than collision-heating.

The hypothesis that protons are heated by hydromagnetic waves up to ~50 $R_\odot$ and cool adiabatically beyond this point, while electrons are effectively heated by thermal conduction out to 1 AU, is not excluded by the observations and deserves further study. Macroscale turbulence is not necessary if the above hypothesis is correct, but local turbulence at positive bulk-speed gradients is still an allowed and likely possibility.

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<u>TABLE 1</u>

Reference	T (^{o}K)	T_e(^{o}K)	T_e/T	V(km/sec)
Wolfe and McKibben (1968)	$\sim 5\times10^{4}$	$\sim 2\times10^{5}$	~ 4	290
Burlaga (1968)	$\sim 2.4\times10^{4}$	$\gtrsim 10^{5}$	$\gtrsim 4$	348
Ogilvie et al. (1968)	$(5.3\pm1.3)\times10^{4}$	$\sim 1.5\times10^{5}$		385
Bame et al. (1969)			3	
Montgomery et al. (1968)	$(4 \text{ to } 10)\times10^{4}$	$(.9 \text{ to } 1.5)\times10^{5}$	1.5 to 3	400
Bame et al. (1969)	$>10^{5}$	$\gtrsim 10^{5}$	~ 1	>400

TABLE II

Date	Time	$T\alpha$	T	$T\alpha/_T$
25 June	0315	3.6×10^5	1.0×10^5	3.6
28 July	1651	5.7×10^5	1.8×10^5	3.2
17 Aug.	0638	8.0×10^5	2.1×10^5	3.8
	0945	8.4×10^5	2.0×10^5	4.2
28 Aug.	0555	5.5×10^5	1.3×10^5	4.2
	0708	6.4×10^5	1.9×10^5	3.3
19 Dec.	0019	8×10^5	2×10^5	4.0
			Mean	3.75

TABLE III

$R_1 (\times 10^{-6} km)$	V (km/sec)	T ($^{\circ}K$)	T(observed) ($^{\circ}K$)
5.4	260	6×10^{3}	1.2×10^{4}
8	320	1.2×10^{4}	3.6×10^{4}
20	410	5×10^{4}	8.5×10^{4}
40	460	1.4×10^{5}	1.3×10^{5}

FIGURE CAPTIONS

Figure 1 This figure shows the number distribution of temperatures, derived from the moments of the line-of-sight velocity distribution, and averaged over 3 hour periods, for the 3000 hours of observations in the interplanetary medium by Explorer 34.

Figure 2a, 2b The bulk speed V and $T^{\frac{1}{2}}$ for the solar wind as observed by Explorer 34 for June to December 1967. The breaks in the data represent periods when the spacecraft was inside the earth's bow shock. Triangles indicate the times of hydromagnetic shocks. Solid bars indicate local heating ($\Delta T > 10^{5\,o}K$).

Figure 3 Values of $T^{\frac{1}{2}}$, computed from three hour averages, plotted as a function of bulk speed V for intervals 250 km/sec^{-1} $< V <$ 300 km/sec^{-1} etc., together with theoretical predictions and other observations as discussed in the text. The open dots are Explorer 34 observations, with uncertainty indicated by error bar on the uppermost point. The solid dots give Parker's solution to the Bernovlli equation for an isothermal corona, $T \propto V^2$.

Figure 4 The number distribution of three hour average values of bulk speed for the ~3000 hours of observations in the interplanetary medium by Explorer 34.

Figure 5 The number distribution of values of ΔT , based upon 3 hour values. The left hand diagram is for negative gradients, the data being broken up into velocity intervals and normalized; this shows no gradient-dependent heating. The

right hand diagrem is for positive gradients. This shows evidence of heating at large speed gradients.

Figure 6 The number distribution of values of ΔT, computed as in Figure 5. The left hand curve is for all the data. This indicates that the heating at positive speed gradients is not a dominant heat source for the interplanetary medium. The right hand curve is for small velocity gradients of either sign $0 < |\Delta V| < 15$ km/sec^{-1}, representing 67% of the data and shows that heating is due to gradients > 15 km/sec.

Figure 7 Number distribution of values of ΔV, the difference between consecutive 3 hour average values of bulk speed, for the interplanetary observations of Explorer 34.

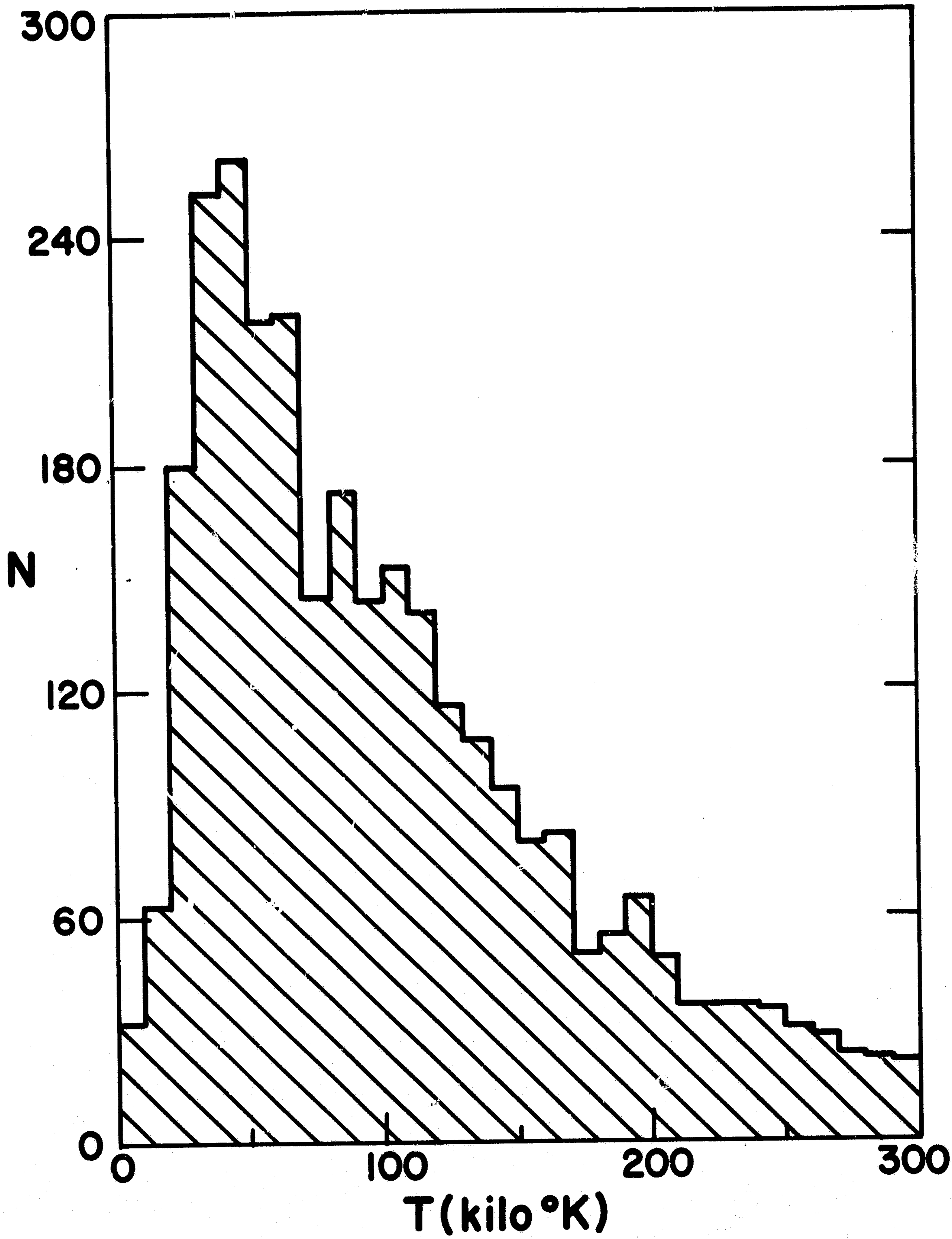
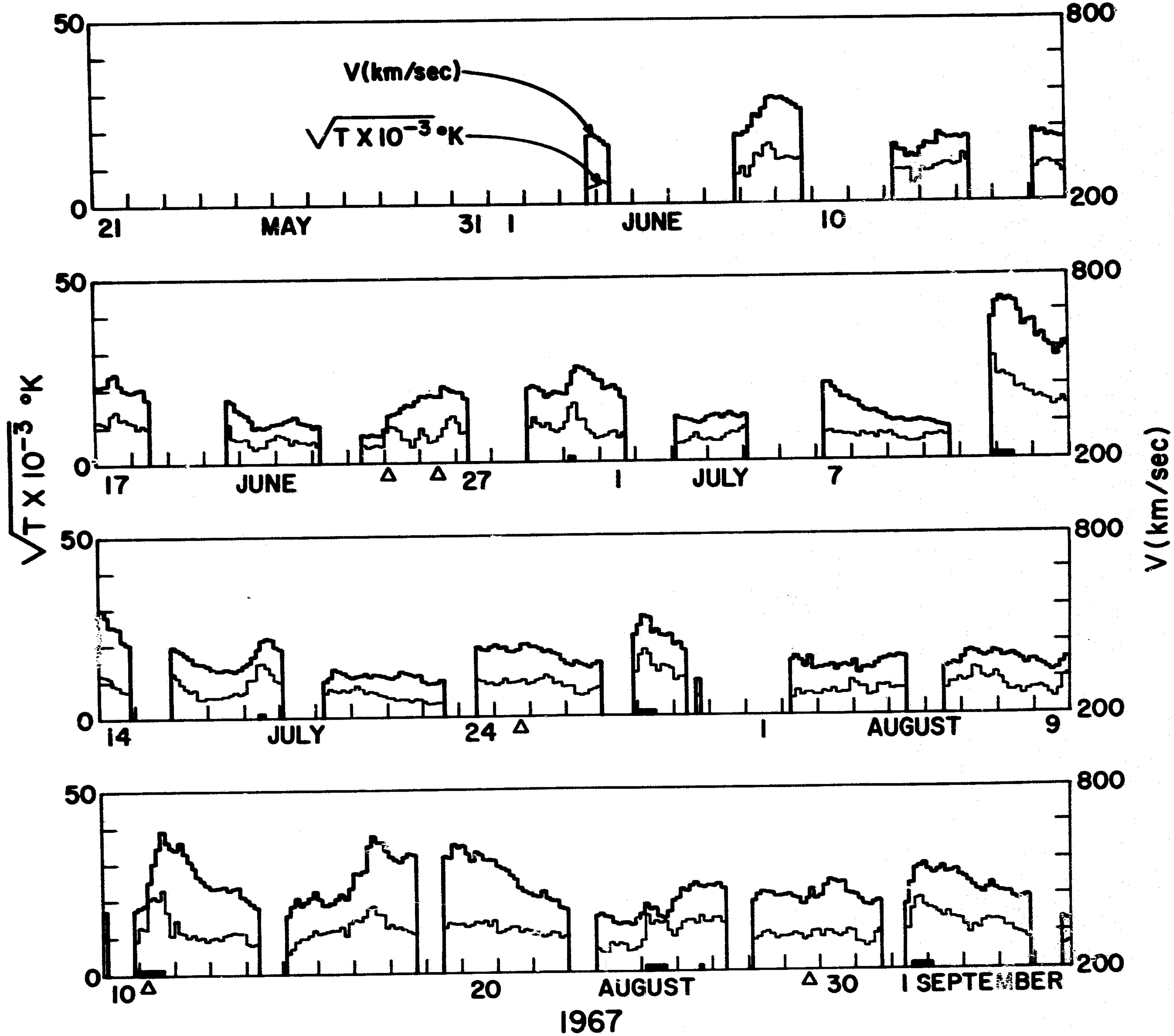


Figure 1



V(km/sec)
$\sqrt{T \times 10^{-3}}$ °K
50
0
800
200
21
MAY
31
1
JUNE
10
17
JUNE
27
1
JULY
7
14
JULY
24
1
AUGUST
9
10
20
AUGUST
30
1 SEPTEMBER
1967
V(km/sec)

Figure 2a

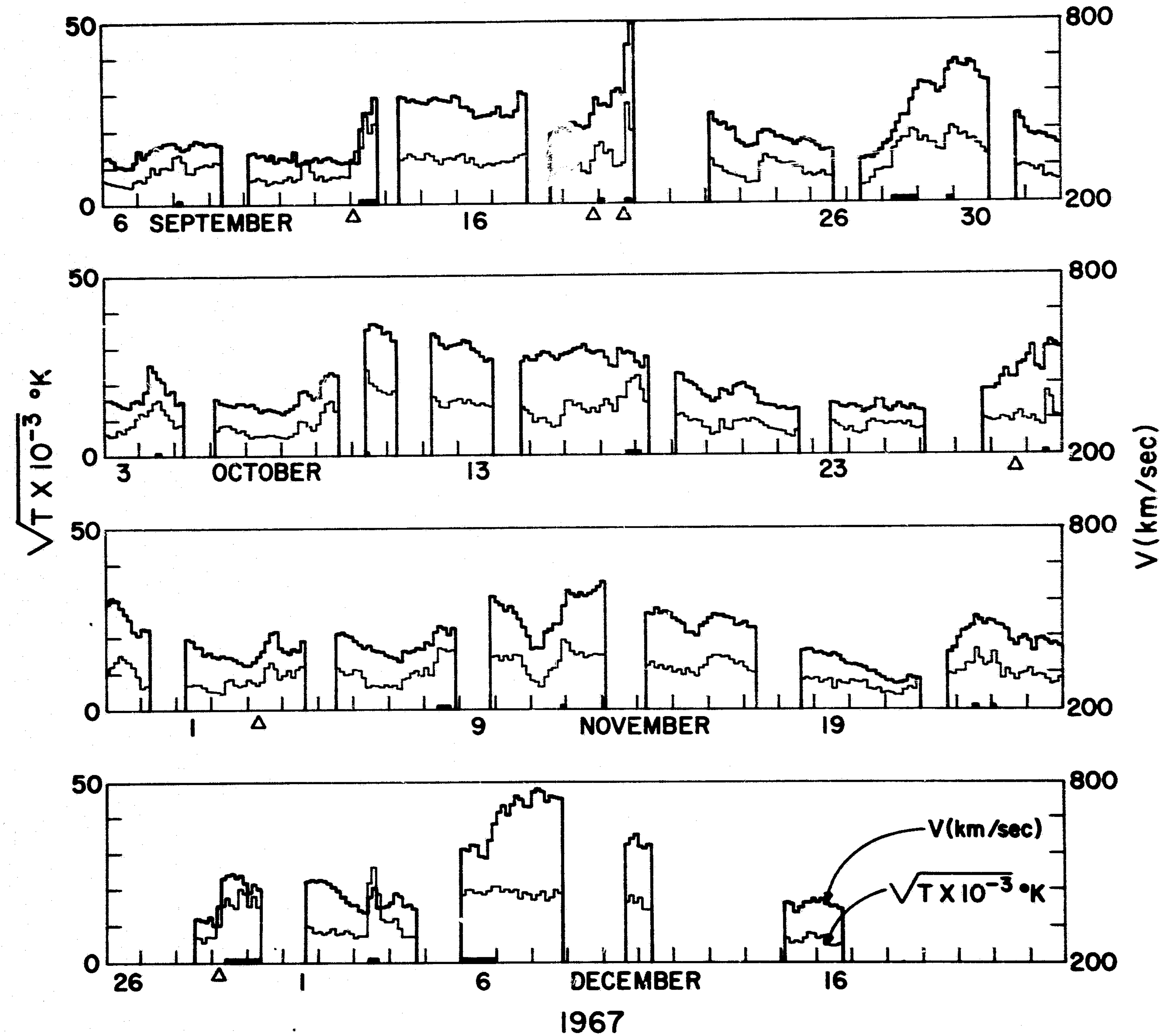
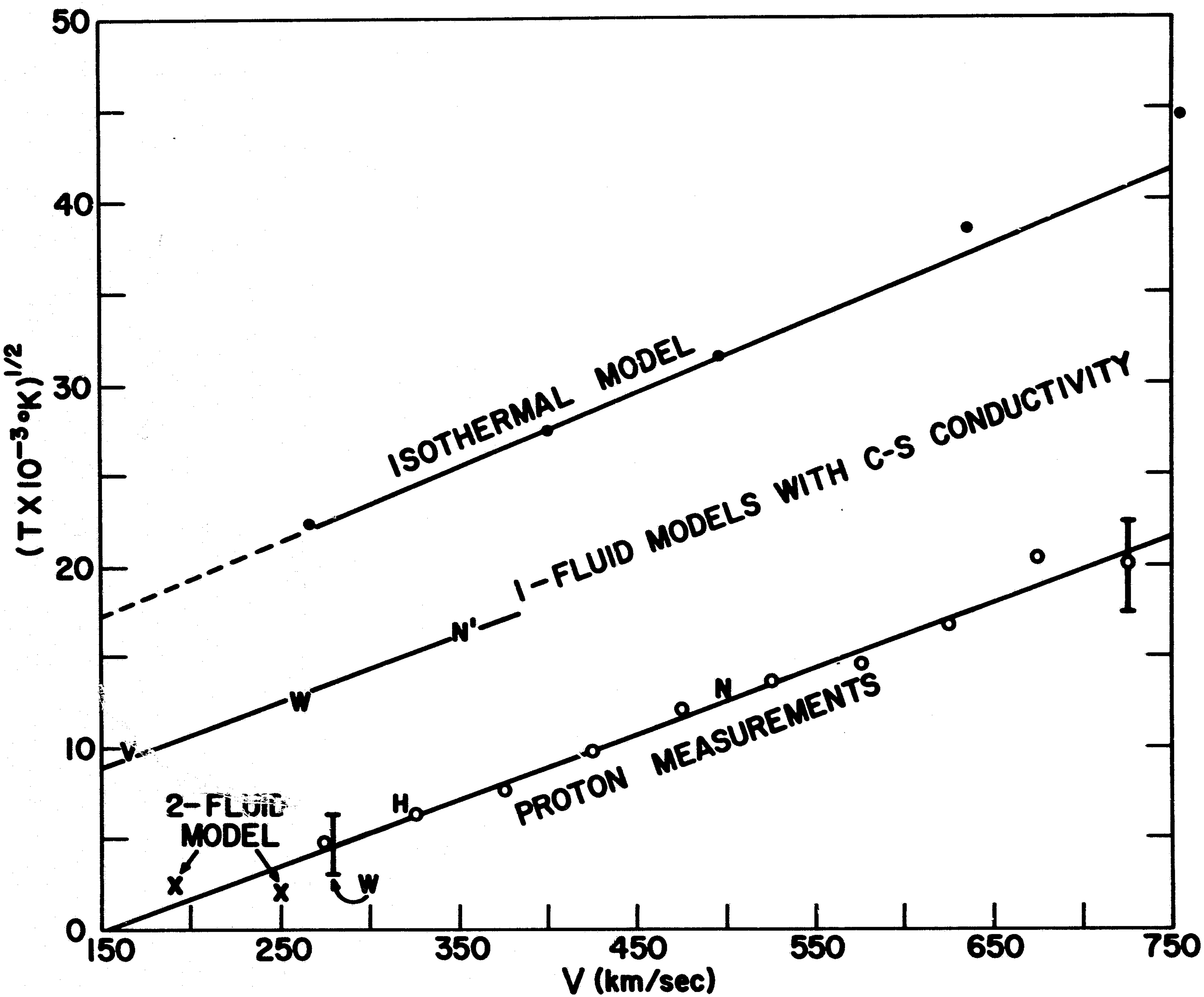

50
0
800
200
6
SEPTEMBER
16
26
30
3
OCTOBER
13
23
1
9
NOVEMBER
19
26
1
6
DECEMBER
16
$\sqrt{T} \times 10^{-3}$ °K
V(km/sec)
1967

Figure 2b



50
40
30
20
10
0
150
250
350
450
550
650
750
$(T \times 10^{-3}\,{}^{\circ}K)^{1/2}$
V (km/sec)
ISOTHERMAL MODEL
1-FLUID MODELS WITH C-S CONDUCTIVITY
PROTON MEASUREMENTS
2-FLUID MODEL
V
W
N'
N
H
X
X
W

Figure 3

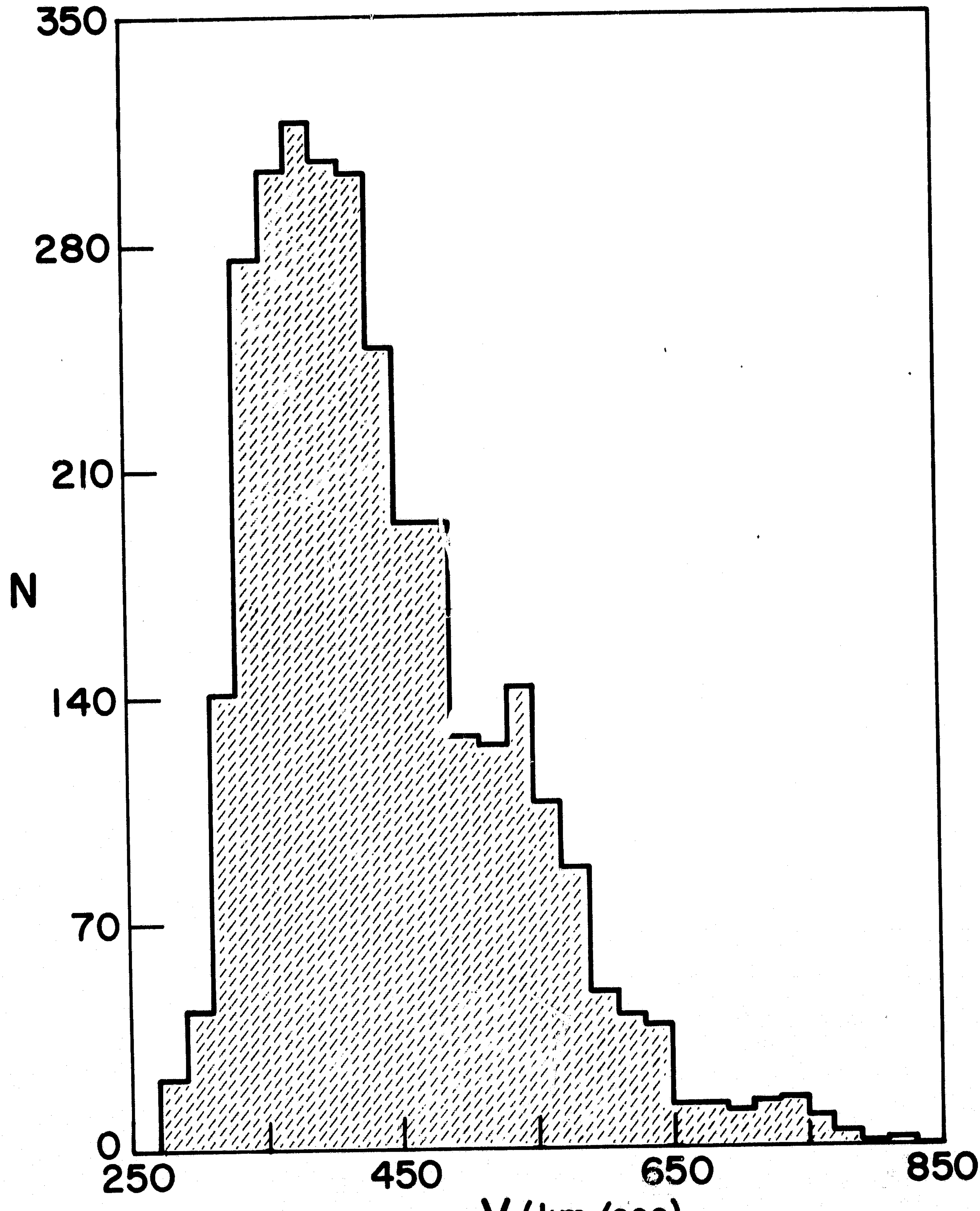
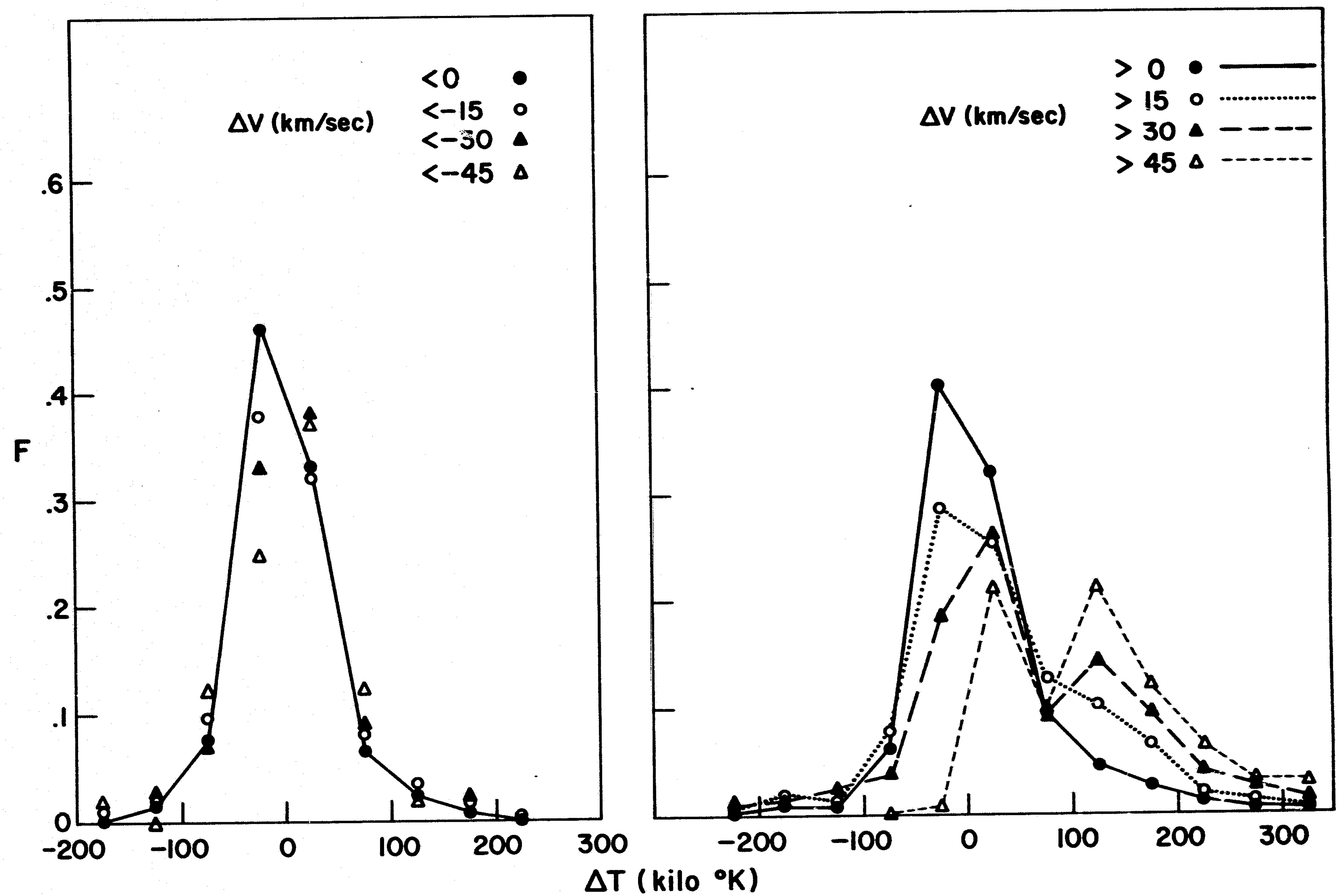


Figure 4



ΔV (km/sec)
<0
<−15
<−30
<−45
ΔV (km/sec)
> 0
> 15
> 30
> 45
F
.6
.5
.4
.3
.2
.1
0
−200
−100
0
100
200
300
ΔT (kilo °K)

Figure 5

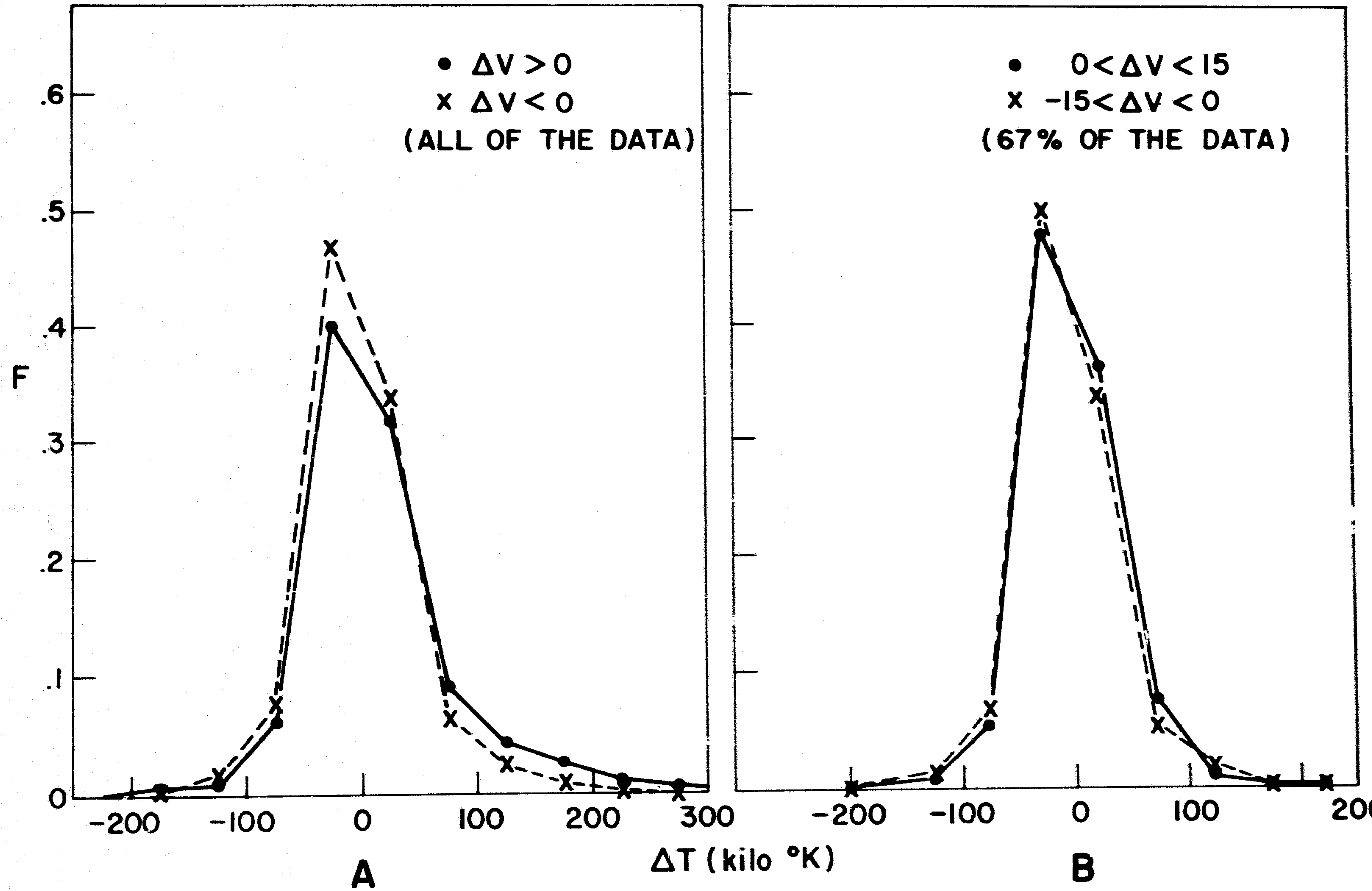

• ΔV > 0
x ΔV < 0
(ALL OF THE DATA)
• 0 < ΔV < 15
x −15 < ΔV < 0
(67% OF THE DATA)
F
.6
.5
.4
.3
.2
.1
0
−200
−100
0
100
200
300
−200
−100
0
100
200
ΔT (kilo °K)
A
B

Figure 6

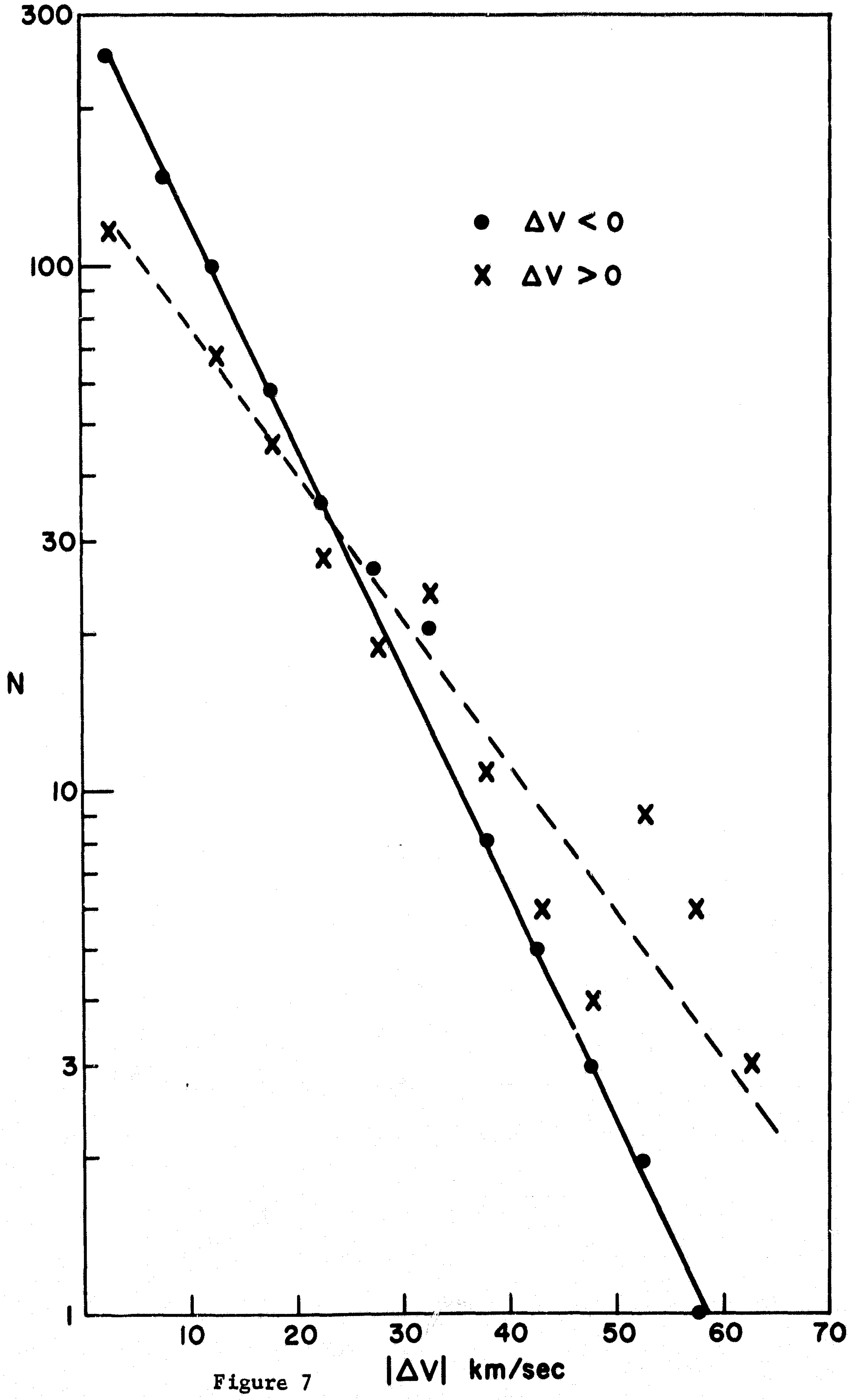


Figure 7